N72-29923

NASA TECHNICAL NOTE

NASA TN D-6917

NASA TN D-6917

ANALYTICAL STUDY OF EFFECT OF CASING TREATMENT ON PERFORMANCE OF A MULTISTAGE COMPRESSOR

by Roger W. Snyder and Robert J. Blade

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1972

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA TN D-6917		

4 Title and Subtitle	5 Report Date
ANALYTICAL STUDY OF EFFECT OF CASING TREATMENT ON PERFORMANCE OF A MULTISTAGE COMPRESSOR	August 1972
	6 Performing Organization Code
7 Author(s) Roger W Snyder and Robert J Blade	8 Performing Organization Report No E-6920
9 Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	10 Work Unit No 764-74
	11 Contract or Grant No
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D C. 20546	13 Type of Report and Period Covered Technical Note
	14 Sponsoring Agency Code

15 Supplementary Notes

16 Abstract

The report presents the results of a simulation study of the effects of casing treament on a multistage compressor. The simulation was based on individual stage pressure and efficiency maps These maps were modified to account for casing treatment effects on the individual stage characteristics. The individual stage maps' effects on overall compressor performance were then observed. The results show that to improve the performance of the compressor in its normal operating range, casing treatment of the rear stages is required

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Casing treatment, Tip treatment; Multistage casing treatment, Axial compressor, Simulation, Compressor boundary layer	Unclassified - unlimited

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price*
Unclassified	Unclassified	25	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

ANALYTICAL STUDY OF EFFECT OF CASING TREATMENT ON PERFORMANCE OF A MULTISTAGE COMPRESSOR

by Roger W. Snyder and Robert J. Blade

Lewis Research Center

SUMMARY

Various experimental programs have indicated that casing treatment can improve the surge margin of axial compressors. These programs, however, have been restricted to single-stage experimental compressors. This report presents the results of a simulation study of the effects of casing treatment on a multistage compressor.

The General Electric J85 compressor was selected for treatment because of the extensive experimental data available. Also, the complete compressor simulation existed from another program. This simulation was based on individual stage pressure and efficiency maps. These maps could be modified to account for casing treatment effects on the individual stage characteristics. The individual J85 stage maps were modified in the same way that casing treatment was observed to modify the stage characteristics in the single-stage experimental programs. The individual stage maps' effects on overall compressor performance were then analytically tested.

A major assumption is involved in this approach. It is assumed that casing treatment affects only the stage characteristics of the stage being treated. The characteristics of the other stages are assumed to remain unaffected. This assumption can only be validated by an actual test program.

The results of this study show that to improve the performance of the J85 compressor in its normal operating range, casing treatment of the rear stages is required. Casing treatment of just the front stages improved only the low-speed operation. Treatment of the rear stages improved the high-speed operation significantly - the stall margin increased from 16.8 to 29.0 percent.

INTRODUCTION

Slots or grooves in an experimental compressor case adjacent to the rotor tips can result in a favorable modification of the rotor-blade pressure-flow field. Testing of a

single-stage compressor (ref. 1) has shown that casing treatment can increase the stage stall margin, flow range, and distortion tolerance. All of these increases are very desirable features. The investigation of the effects of casing treatment on a multistage compressor is thus a logical outgrowth of the experimental program.

The General Electric J85 compressor was selected for this investigation because of its simplicity and the existence of considerable analytical and experimental information. Having chosen the compressor, it was necessary to decide how many and which stages would be treated. To assist in this selection, an analytical study was conducted to determine the effect of casing treatment of various stages on overall compressor performance. The assumptions, the method, and the results of this study are discussed herein.

This report is broken down into sections. First, a short description of the single-stage casing-treatment experiments is presented to introduce the subject to readers unfamiliar with the technique. A more detailed description of the single-stage experiments is presented in references 1 to 3. Next is a discussion of the stage-by-stage dynamic model of the J85 compressor. This model was used as the basis for the analysis. Then, the main body of this report describes the modification of the J85 stage characteristics to account for the effects of casing treatment. And finally, the analytical results are described.

Up to now, only single rotors and single stages have been experimentally studied with casing treatment. Various casing designs of slots, grooves, and holes have been tried. However, no experimental work on multistage casing treatment has been performed to date.

EXPERIMENTAL STUDIES OF CASING TREATMENT

A single-stage axial compressor (rotor 5 test program - see ref. 1) was tested at the Lewis Research Center with various casing treatments across the rotor tips. The rotor was designed to be highly tip loaded. Casing treatment thus should alter this compressor's characteristics to a greater extent than in most designs. The casing treatments actually tried included a solid casing (the standard engine configuration), a skewed-slot casing, a circumferentially grooved casing, and three different blade-angle-slot casings. The circumferentially grooved casing and the three different blade-angle-slot casings are shown in figures 1 and 2. These figures give some indication of the design range possible with casing treatment.

All of the casing treatments significantly improved the operating flow range over that of the solid casing. The skewed slots and blade-angle slots seem to improve stall margin the most (see fig. 3). The solid-casing flow range was from choke at approximately 30 kilograms per second down to stall at 29 kilograms per second for an operating

range of about 4 percent of maximum flow. In contrast to this, the skewed slots produced a stable flow range of approximately 15 percent of maximum flow. And peak pressure ratio improved from 1.8 with the solid casing to 1.9 in the skewed-slot casing.

In reference 3, four empirically determined parameters were found to control the effectiveness of casing treatment: (1) Axial extent, (2) open area, (3) depth or volume, and (4) amount of recirculation. Casing treatments to be successful required that the following conditions be met. (1) The axial extent of treatment must be limited to a dimension less than the axial projection of the blade chord. (2) The open area must be at least two-thirds of the total area treated. (3) As the depth or volume of the treatment increases, the useful flow range is extended. (4) The recirculation from the downstream high pressure region to the upstream low pressure region must be limited. Recirculation is effective in delaying rotating stall but an excess can cause undue loss in efficiency.

It appears that rotors with a narrow operating flow range can be improved the most. Rotors which have a broad flow range can be improved only slightly. This is not surprising, since the rotor which is more refined to start with could be expected to have less improvement potential. With all rotors, casing treatment seems to extend the rotor speed lines to lower flow rates before stall occurs. The degree of surge-margin improvement varies with rotor design (i.e., highly tip loaded designs seem more improvable) and also with the type of casing treatment. The pressure ratio, however, is sometimes increased, sometimes decreased, again depending on the type of casing treatment. Surge-margin improvement is by far the most important effect of casing treatment studied here. Distortion-tolerance improvement could be very important but could not be investigated in this simulation study.

DESCRIPTION OF SIMULATION MODEL

Simulation of the J85 compressor used in this analysis is based on the methods presented in references 4 and 5. The model is based on individual stage-by-stage steady-state characteristics. These are coupled through the gas dynamics of the associated stage volumes. A schematic of an idealized stage is shown in figure 4.

For analysis, the compressor is divided, stage-by-stage, into lumped volumes. The analysis assumes that each stage, consisting of a rotor, a stator, and the included volume, can be modeled by an actuator disc coupled to the gas dynamics of a lumped volume. At the front face of each volume are inserted the pressure and temperature characteristics of that individual stage. This method is similar to the actuator disc technique of analyzing cascades in that all cascade or blade effects are concentrated at the boundary lines. This simulation technique must be considered quasisteady because it im-

plicitly assumes that the steady-state stage maps are valid during the transient excursions of the compressor.

The steady-state performance of a multistage compressor can be represented by pressure and temperature rise coefficients ψ^P and ψ^T of the individual stages. Both ψ^P and ψ^T are functions of the flow coefficient φ. The stage maps for the unmodified J85 compressor are shown in figure 5. Figure 5(a) presents the maps for stages 2 to 8, which are independent of speed. Figure 5(b) gives the pressure-coefficient map at 80 percent and 100 percent corrected speeds for stage 1. The stage-1 maps shift with speed because of the effect of the variable inlet guide vanes. The stage parameters are defined by the following equations. The symbols used in the equations are defined in the appendix.

$$\psi_n^P = \frac{C_n T_{v,n-1}}{N^2}\left[\left(\frac{P_{c,n}}{P_{v,n-1}}\right)^{(\gamma-1)/\gamma} - 1\right]$$

$$\psi_n^T = \frac{C_n}{N^2}(T_{c,n} - T_{v,n-1})$$

$$\varphi_n = \frac{k_n}{N} V_{z,n}$$

where the constants are given by

$$k_n = \frac{1}{2\pi r_n}$$

$$C_n = 2g_c J C_P k_n^2$$

An equation relating V_z to stage-inlet total pressure and temperature is developed in reference 5. Their final equation is

$$\frac{W_{c,n}\sqrt{\left(\frac{T_{v,n-1}}{T_r}\right)}}{A_n\left(\frac{P_{v,n-1}}{P_r}\right)} = \frac{V_{z,n}}{\sqrt{\left(\frac{T_{v,n-1}}{T_r}\right)}}\left\{1-\left[\frac{V_{z,n}}{\sqrt{\left(\frac{T_{v,n-1}}{T_r}\right)}}\right]^2\frac{1}{2gJC_pT_r\cos^2\beta}\right\}^{1/(\gamma-1)}\rho_{tr}$$

The above implicit equation for V_z takes into account that the flow function φ needs static pressure and temperature, whereas the simulation generates total quantities. Also, the Mach number is a function of total velocity and not just of the axial component V_z.

The dynamic response of the compressor is described by the conservation equations of the volume elements. These gas dynamics are described by three conservation equations and an equation of state. Reference 4 presents a complete derivation of these equations. The following is the final set of finite-differenced equations for the n^{th} volume lump:

Mass conservation

$$\frac{d}{dt}(\rho_{v,n}) = \frac{1}{L_nA_n}(W_{v,n} - W_{v,n+1})$$

Momentum conservation

$$\frac{d}{dt}(W_{v,n}) = \left(\frac{Ag}{L}\right)_n\left(1+\frac{\gamma - 1}{2}M_{v,n}^2\right)^{\gamma/(\gamma-1)}(P_{c,n} - P_{v,n})$$

Energy conservation

$$\frac{d}{dt}(\rho_{v,n}T_{v,n}) = \frac{\gamma}{L_nA_n}(T_{c,n}W_{v,n} - T_{v,n}W_{v,n+1})$$

Equation of state

$$P_{v,n} = R\left(1+\frac{\gamma - 1}{2}M_{v,n}^2\right)^{1/(\gamma-1)}\rho_{v,n}T_{v,n}$$

SIMULATION OF CASING TREATMENT

The compressor simulation uses individual stage maps. The influence of casing treatment is included by modifying these stage maps. Casing treatment affects a stage map in different ways depending on the type of treatment. Some uncertainty exists concerning the effects of casing treatment on stage efficiency. Therefore, the efficiency maps were left unchanged. Figure 6 shows some representative experimental stage maps obtained during the rotor 5 test program conducted at the Lewis Research Center (see ref. 2) The profile obtained from the standard untreated compressor is included for reference. Comparison of the curve representing the circumferentially grooved casing with the curve representing the standard solid casing shows that the stall pressure ratio can be raised and that the flow range can be increased by 250 percent. The difference between the two curves in the region of the solid-casing curve is not regarded as being experimentally signficant. The curve representing the casing with the skewed slots shows an even greater improvement (450 percent) in flow range over that of the solid casing. And while the stall pressure ratio shows some improvement over that of the unmodified (solid) casing, the pressure ratio in the region of the solid-casing curve is decreased. The study of such a wide range of casing treatment effects makes analysis somewhat difficult. In this study, the technique of analysis chosen was to identify some of the extreme cases and calculate a range of possible effects.

The effects incorporated into the J85 stage maps were somewhat larger than those obtained by the Lewis Research Center's rotor 5 test program. For the present investigation, we wanted to make the multistage effects obvious. Therefore, the individual stage adjustments were made as large as seemed reasonable. In justification, it is very unlikely that the limited number of casings experimentally investigated to date have established the maximum pressure-ratio boost. It is reasonable to expect that future casing treatments will improve upon the past results. Furthermore, smaller casing-treatment effects could be interpolated from this one set of trials with reasonable assurance, whereas extrapolation has much less certainty of being accurate.

The J85 stage pressure maps were modified in the manner experimentally observed in the single-stage studies. The efficiency maps were left unchanged. Figure 7 shows some typical front-stage modifications. To the right of the normal operating point for 100-percent corrected speed (i.e., in the higher flow region), the modified curve is assumed to be lower than the unmodified curve. To the left of this normal operating point, various higher pressure coefficients were assumed.

Two different ψ^{P}-φ curves were considered for the low flow region to the left of the normal operating point (see fig. 7). The upper curve simply extends the stage map asymptotically to a maximum pressure coefficient. This curve is representative of some of the rotor 5 data. Rotor 5 shows the flow range extended in the low flow direction with no sign of the curve bending over to a positive slope. This modification repre-

sents the extreme case where the ψ^P-φ curve never attains a positive slope and will be referred to herein as the zero-slope modification.

The middle curve of figure 7 allows a positive slope for the ψ^P-φ curve and will be referred to herein as the positive-slope modification. This is the more likely case. The rotor-5 tests were performed on single-stage machines. As soon as the single-stage compressor operated on the positive slope, the test ended with the entire test rig surging. This would not necessarily occur with a multistage compressor, since there likely would be other stages to hold the entire system out of surge until many stages had peaked over to positive slopes.

The positive-slope casing treatment was assumed to increase the maximum pressure coefficient by approximately 10 percent over the standard maximum pressure coefficient. At the same time, this higher maximum pressure coefficient was assumed to occur at approximately 10-percent lower flow coefficient. This change reasonably resembles observed single-stage data except for the postulated improvement of a positive slope. These various front-stage modifications (i.e., stages 1 to 3) are compared in figures 8 and 9. Figure 8 compares the stage-1 maps used for 80- and 100-percent corrected speed. Figure 9 compares the maps used for stages 2 and 3.

A typical rear-stage casing-treatment modification is shown in figure 10. Here, treatment is assumed simply to extend the zero-slope line to flows below the unmodified compressor abrupt surge point. This variation was used for all examples of rear-stage casing treatment in the present study.

A major assumption in the overall analytical approach is that casing treatment affects only the stage map of the individual stage being treated. The following stage maps are assumed to be completely unaffected by the casing treatment upstream. Flow-profile measurements in single-stage tests seem to show that some casing treatments alter the tangential velocity and temperature profiles in the tip region. This alteration most likely "washes" downstream to other stages in a multistage compressor. Single-stage data show the effect on the treated stage, but, of course, can indicate nothing about the effect on neighboring stages, since there are none. Interaction data do not exist at present; these must come from multistage experimental tests.

PERFORMANCE CRITERIA

The performance of the compressor after modification was judged according to three criteria - surge margin, pressure ratio, and overall efficiency.

Surge margin is defined as follows:

$$\text{Percent surge margin} = \frac{\left(\dfrac{P_3/P_2}{W_2}\right)_{\text{surge}} - \left(\dfrac{P_3/P_2}{W_2}\right)_{\text{oper. point}}}{\left(\dfrac{P_3/P_2}{W_2}\right)_{\text{oper. point}}} \times 100$$

Since surge margin is one of the most important performance criteria, a brief explanation will be made here of how surge is identified. Simulation is started for a particular compressor operating point. After a few time steps, a perturbation is made in the exit-nozzle flow area. This causes the pressure and flow to readjust throughout the compressor with a resulting transient oscillation. If this transient dies out, it is assumed that the compressor is operating on the stable side of the surge line. If the transient grows, it indicates operation in the surge region.

Pressure ratio P_3/P_2 is simply a ratio of the compressor back-face to front-face total pressure.

Overall efficiency could be defined in various ways. Herein it is defined as

$$\eta = \frac{W_{isen}H_{isen} - W_2H_2}{W_{out}H_{out} - W_2H_2}$$

where W_{isen} equals W_2, and $W_{out}H_{out}$ includes bleed flows. This is just

$$\frac{\text{Useful energy}}{\text{Total energy}} = \eta = \frac{\left(\dfrac{P_3}{P_2}\right)^{(\gamma-1)/\gamma} - 1}{\left(\dfrac{W_3}{W_2}\right)\left(\dfrac{T_3}{T_2}\right) + \dfrac{W_{bleed}T_{bleed}}{W_2T_2} - 1}$$

DESCRIPTION OF SIMULATION RUNS

Various casing-treatment configurations were simulated in this program; however, only three types of variations were studied in depth. First, different ψ^P-φ map profiles were tried. Second, different stages were treated, at either the front or the rear of the compressor. And finally, flow from the third-stage variable bleeds was blocked. These various stage-map and bleed modifications are listed in table I. Also included in the table are the resulting values of the surge-margin performance criterion.

TABLE I - CODIFICATION OF CASING TREATMENTS OF J85 COMPRESSOR

Case	Modification			Surge margin at 100-percent speed, percent
	Stages 1, 2, and 3	Stages 7 and 8	Third-stage bleed	
Reference	Unmodified	Unmodified	Unmodified	16 8
1	Zero slope	Unmodified	Unmodified	17 4
2	Unmodified	Zero slope	Unmodified	29 0
3	Zero slope	Zero slope	Unmodified	38 7
4	Zero slope (80-percent speed)	Unmodified	Blocked	----
5	Positive slope	Zero slope	Unmodified	32 3

Which stage or stages are to receive the casing treatment is very critical. Not surprisingly, the overall compressor performance depends greatly on which stage received the modified maps. In case 1, only the maps of stages 1, 2, and 3 were adjusted, since these are the stages most easily accessible for hardware modification. The modified stage maps actually used for case 1 are presented in figures 8 and 9.

The results of the case 1 variation are compared with those of the standard compressor in figure 11. In this figure, and also in figure 12, the solid symbols denote the points at which the simulation indicates that surge occurs. These figures clearly indicate that treating just the front stages is not sufficient. This attempt to improve the J85 compressor appears only slightly successful, as the surge margin was only increased from 16.8 to 17.4 percent. At high rotor speeds, compressor surge is caused by the last stages while the front stages still are running fairly effectively. Surge at 100-percent corrected speed is caused probably by the abrupt stalling of stage 7 or 8. This trips the entire compressor into surge. Treatment of the front stages helps more at 80-percent speed and below. Unfortunately, an aircraft engine seldom operates at speeds as low as 80 percent. Therefore, the pressure-ratio maps for the rear stages were adjusted for casing treatment to study if surge margin could be improved at 100-percent speed (cases 2 and 3).

Treating the rear stages extended the surge margin of the overall compressor by 12.2 percent over that of the unmodified case. Figure 11 compares the unmodified case with three different variations - only front stages treated (case 1), only rear stages treated (case 2), and rear and front stages both treated (case 3). This figure shows that modifying only the front stages does increase slightly the surge margin or efficiency. Modifying only stages 7 and 8 results in an improvement in flow range from 0.18 to 1.2

kilograms per second, or a 12.2-percent increase in stall margin. When stages 7 and 8 are modified, then modifying the front stages will give even more improvement, since the range is extended to such an extent by modification of the back stages that the front stages are finally pushed to their limit, and therefore are amenable to modification also. Modifying front and back stages results in a flow range of 1.8 kilograms per second, or a 21.9-percent increase in stall margin.

Finally, flow from the third-stage bleed was blocked in conjunction with tip treatment of the first 3 stages (i.e., case 4) The only advantage of doing this appears at lower speeds, since the bleeds are completely closed anyway at speeds greater than about 95 percent. At 80-percent speed, where the bleeds are fully open, bleed-flow blockage has major effects, as can be seen in figure 12. As it developed, casing treatment of the front stages made it possible to cut third-stage bleed flow and still operate without surge. Simulation runs not reported herein have shown that other stage bleeds can be blocked, but with much more reduction in surge margin. The advantage of blocking third-stage bleed is that compressor efficiency is greatly increased (9-percent increase at the peak efficiency points). The reason for the large increase in compressor efficiency is that the compressor is no longer required to do work on fluid which later is bled overboard. Surge margin obtained from casing treatment has been traded to allow bleed-flow blockage. These results indicate that casing treatment could considerably reduce the need for bleeding the J85 casing-treated compressor.

However, it must be remembered that this study does not take into account blade-vibration problems which could be encountered. The simulation only considers the fluid dynamics; mechanical stress is not considered.

The positive-slope type of casing treatment takes into account the probability that the J85 stage maps will still have positive slopes, even after casing treatment. Case 5 has stages 1, 2, and 3 modified with positive slope treatment (see figs 8 and 9), while stages 7 and 8 use the zero-slope treatment (fig. 10)

In figure 13, case-5 casing treatment is compared with the standard compressor and the case 2 compressor. Not surprisingly, the improvement obtained with case 5 is less pronounced than that obtained with case 1 (compare figs. 11 and 13). Surge margins obtained with all the various modifications are compared in table I. The normal operating point of the engine system is assumed the same for each case (i.e., overall pressure ratio of 6.8 and flow rate of 19.9 kg/sec). In other words, in the calculation of the surge margin, the normal operating point is assumed to be unchanged by casing treatment.

A casing modification shifts the point at which each stage operates for a given speed. Figure 14 shows the stage maps with the normal operating points for 80-, 90-, and 100-percent corrected speed plotted on it. Stage-1 data were omitted to simplify the figure. The most interesting thing to note is that the stages appear to swing around stage 3

as the speed is increased. The rear stages (4 to 8) move closer to stall (towards the left in fig. 14) as 100-percent corrected speed is approached; stages 1 and 2 move away from stall (towards the right in fig. 14). This is why, as 100-percent speed is approached, the rear stages are the critical stages to be improved by casing treatment.

If the speed is fixed at 100 percent and instead the flow rate is varied from the normal operating point, the results obtained for the unmodified compressor are those shown in figure 15(a). For the case-5 compressor, the stall points of the various stages were all shifted to much lower flow rates (see fig. 15(b)). Thus it can be concluded that flow range can be improved considerably with this case-5 change.

CONCLUDING REMARKS

Past experiments with single-stage casing treatment need to be extended to multistage compressors. The GE J85 8-stage compressor looks attractive as a test bed. It is a relatively simple compressor and has been extensively tested and analyzed here at the Lewis Research Center.

The simulation described in this report points out one important fact. If it is desired to improve the J85 in its normal operating range, it must have the rear stages casing treated. Casing treatment of the front stages will improve only the low-speed operation of the compressor. However, if the rear stages are modified, then casing treating the front stages will further improve the results.

Results of this simulation study are tempered by the various assumptions which were made. It was assumed that steady-state stage maps would be valid during surge or stall. Also, it was assumed that casing treatment would affect only the stage map of the individual stage being treated and would not cause flow-profile changes which would wash downstream to the next stage.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 26, 1972,
764-74.

APPENDIX - SYMBOLS

A	area, m^2
C	stage-map constant, Hz^2/K
C_p	specific heat of air at constant pressure, J/(kg)(K)
g_c	gravitational constant, (kg)(m)/(N)(sec^2)
J	mechanical equivalent of heat, (N-m)/J
k	constant, revolutions/meter
L	length of stage lump, m
M	Mach number
N	compressor speed, rps
P	total pressure of fluid, N/m^2
R	gas constant, J/(kg)(K)
r	radius, m
T	total temperature of fluid, K
V	velocity, m/sec
W	mass flow rate, kg/sec
β	absolute air angle of fluid entering stage, deg
γ	specific-heat ratio
δ	ratio of total pressure to standard sea-level pressure
η	efficiency
θ	ratio of total temperature to standard sea-level temperature
ρ	static density of fluid, kg/m^3
φ	stage flow coefficient
ψ^P	stage pressure coefficient
ψ^T	stage temperature coefficient

Subscripts:

c	compressor map variable
isen	isentropic condition
n	stage number

norm	normalizing parameter
r	reference condition
t	total condition
v	stage volume variable
z	axial direction
2	front face of compressor
3	back face of compressor

REFERENCES

1. Moore, Royce D.; Kovich, George; and Blade, Robert J.: Effects of Casing Treatment on Overall and Blade-Element Performance of a Compressor Rotor. NASA TN D-6538, 1971.
2. Osborn, Walter M.; Lewis George W., Jr.; and Heidelberg, Laurence J.: Effect of Several Porous Casing Treatments on Stall Limit and on Overall Performance of an Axial-Flow Compressor Rotor. NASA TN D-6537, 1971.
3. Anon.: Aircraft Propulsion. NASA SP-259, 1971.
4. Seldner, Kurt; Mihaloew, James R.; and Blaha, Ronald J.: A Generalized Simulation Technique for Turbo-Jet Engine System Analysis. NASA TN D-6610, 1972.
5. Willoh, Ross G.; and Seldner, Kurt: Multistage Compressor Simulation Applied to the Prediction of Axial Flow Instabilities. NASA TM X-1880, 1969.

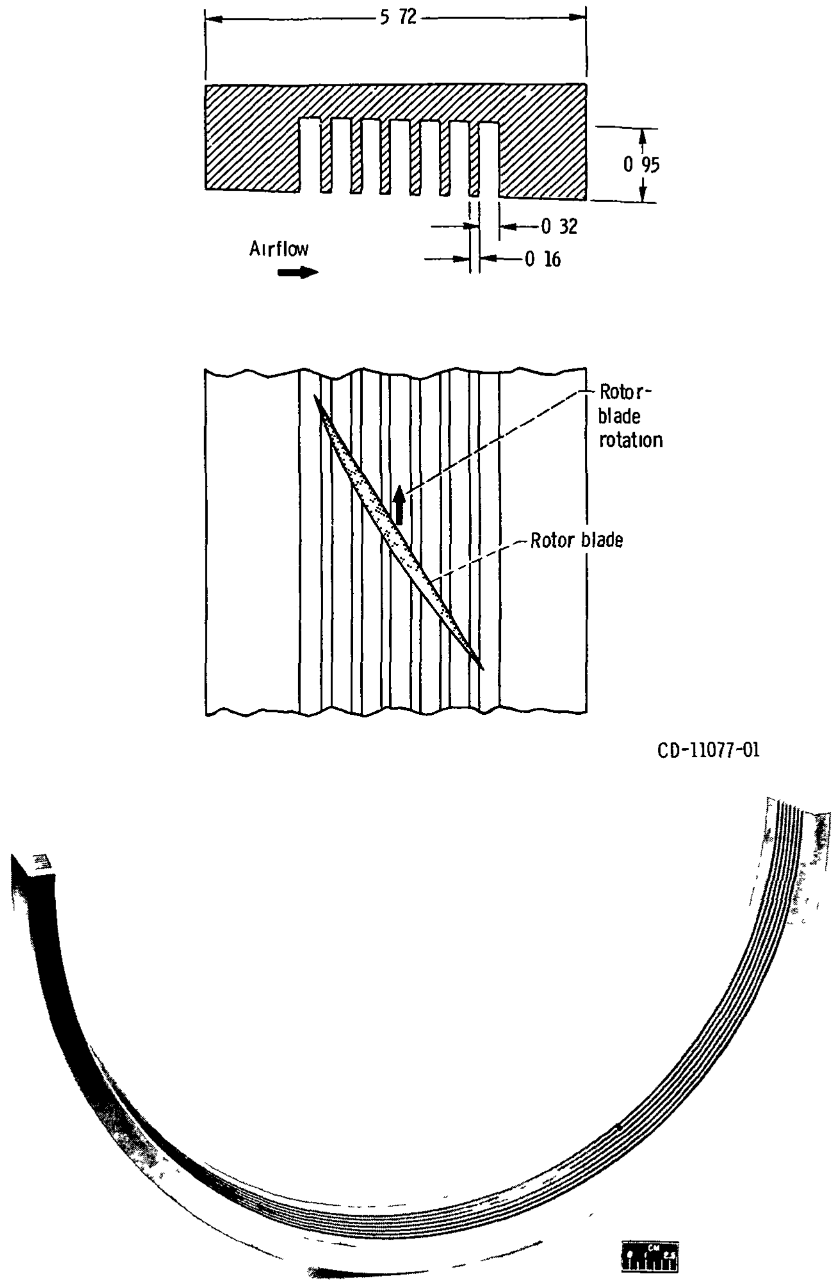

Figure 1 - Circumferential-groove insert Dimensions in centimeters

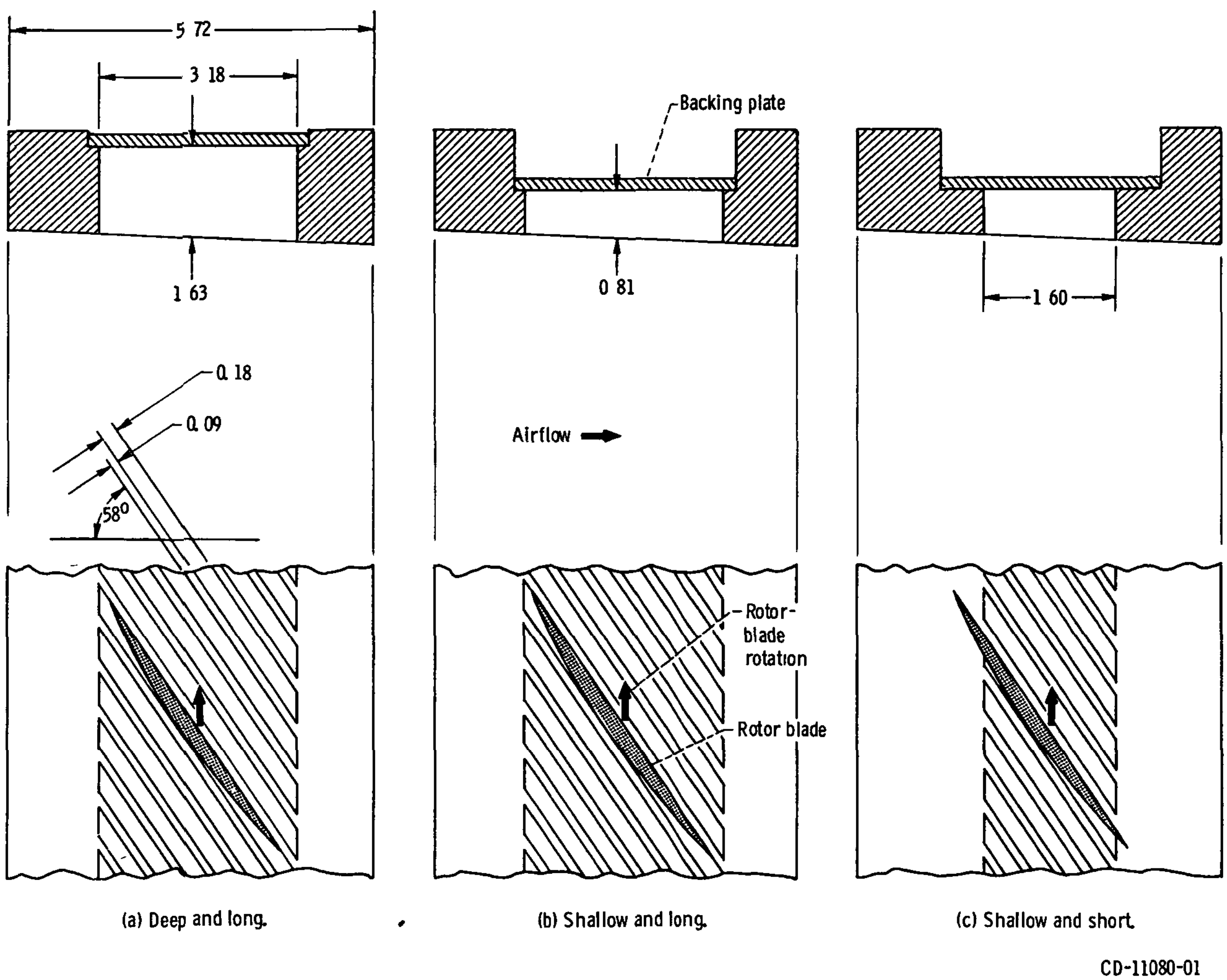

Figure 2. - Blade-angle-slot inserts. Dimensions in centimeters.

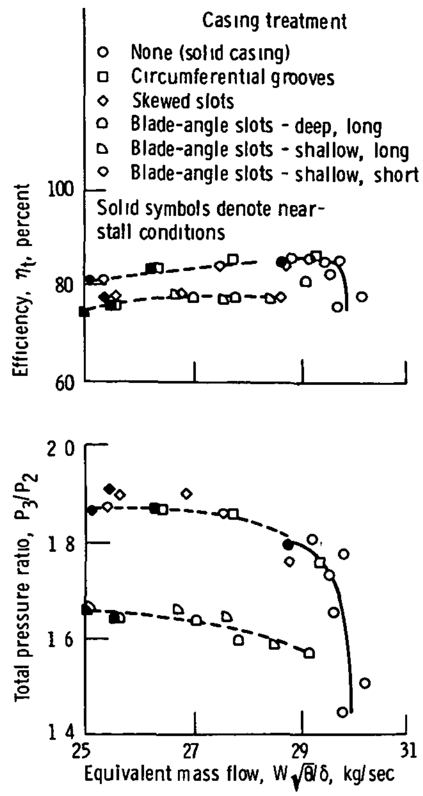

Figure 3 - Effect of casing treatment on the overall performance of rotor 5 at 100-percent design speed

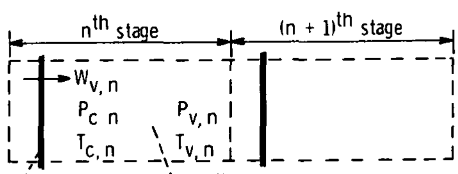

Figure 4 - Diagram of n^{th} stage of compressor

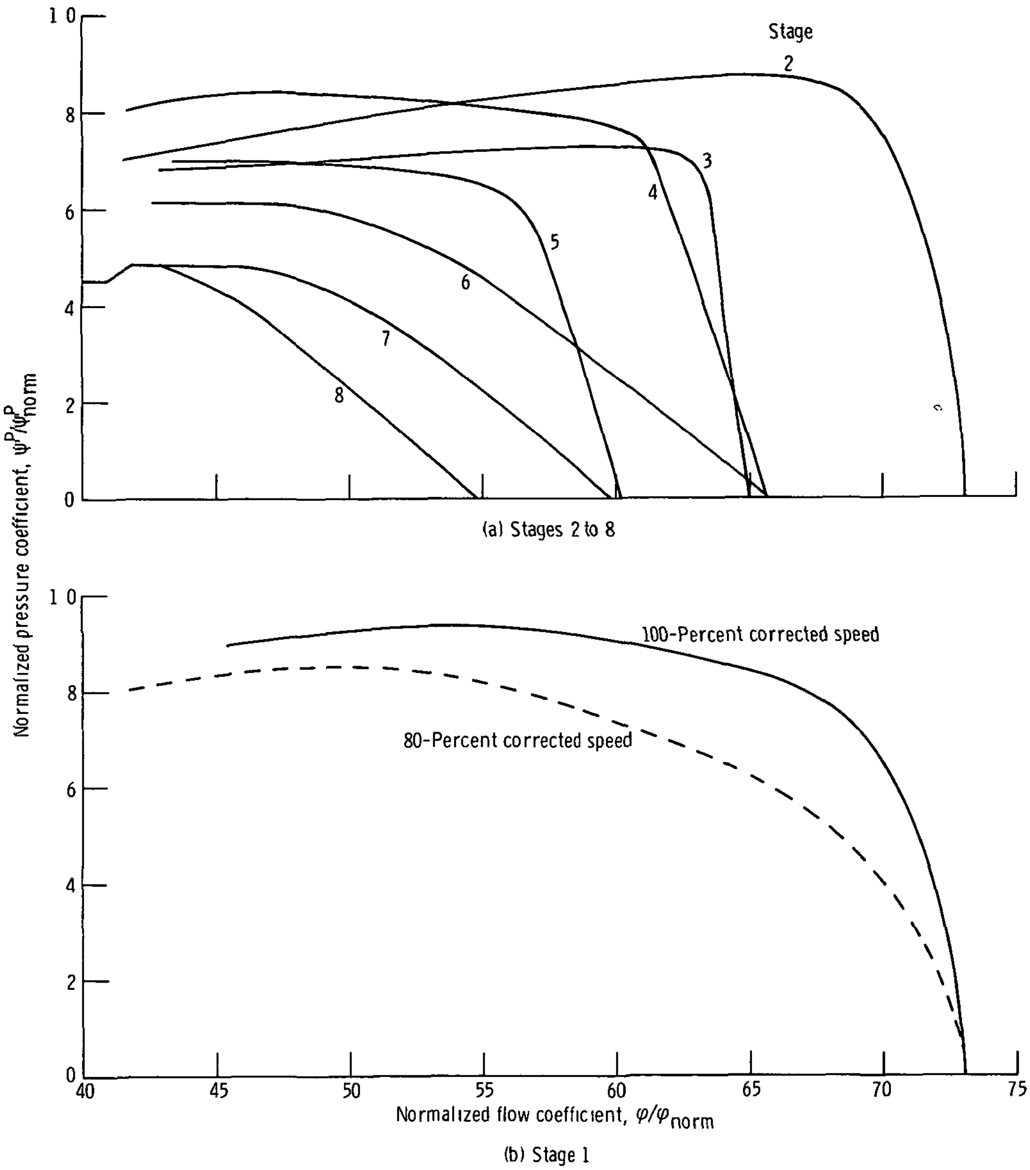

Figure 5 - Unmodified stage maps for J85 compressor

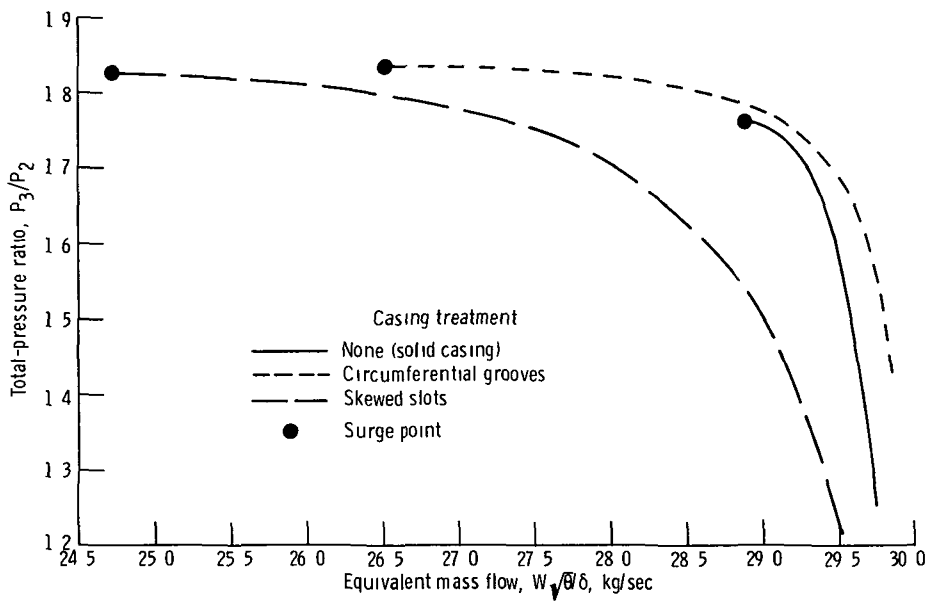

Figure 6 - Representative experimental stage maps for rotor 5

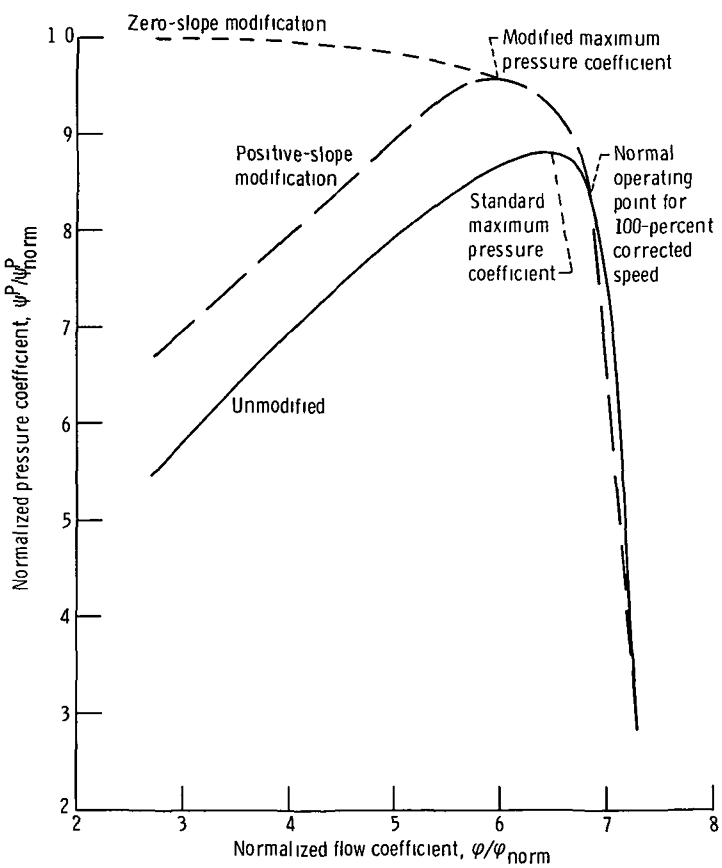

Figure 7 - Typical front-stage modifications for J85 compressor

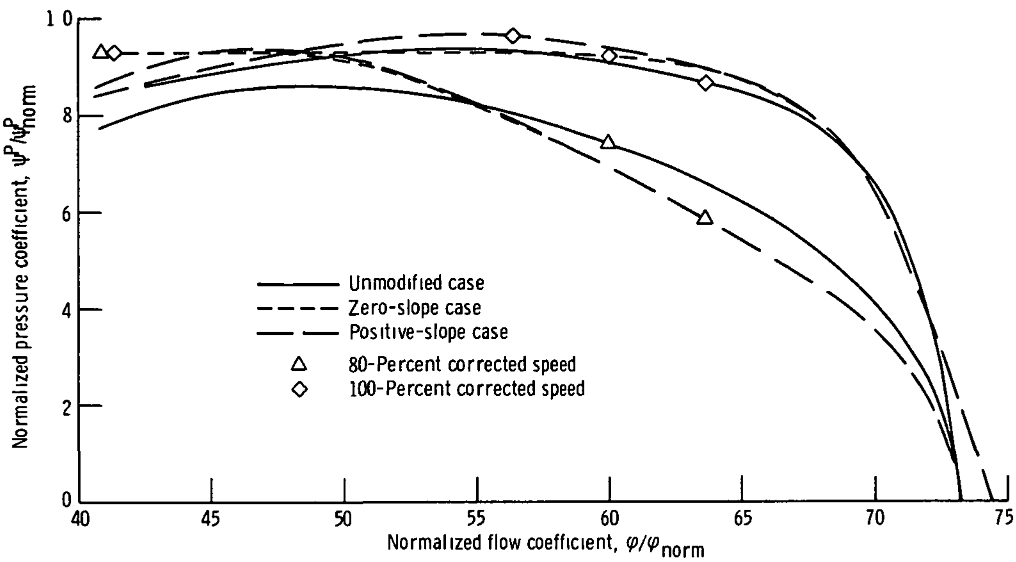

Figure 8 - Stage-1 modifications for J85 compressor

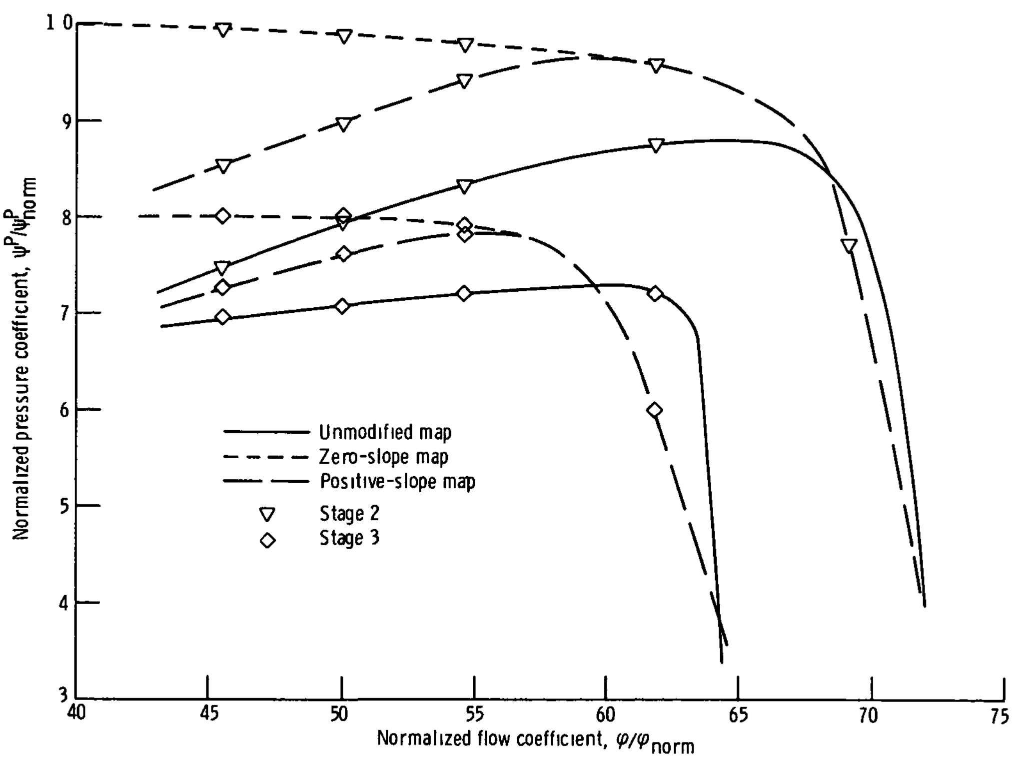

Figure 9 - Modified stage 2 and 3 maps for J85 compressor

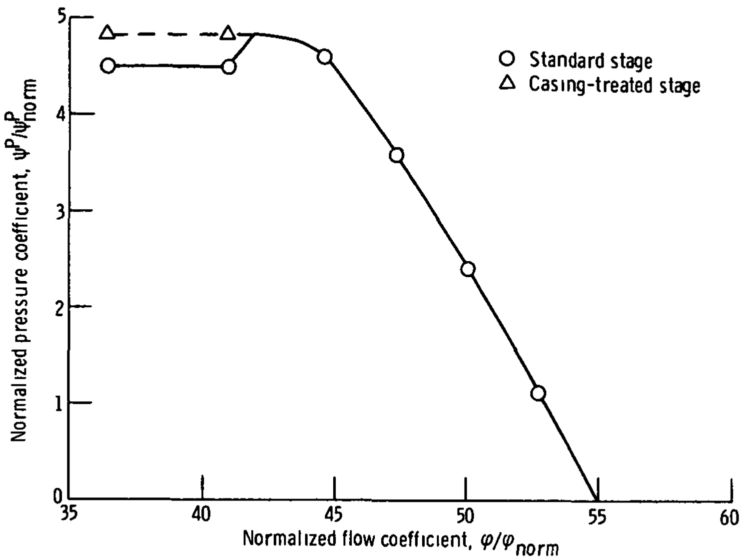

Figure 10 - Typical rear-stage modification for J85 compressor

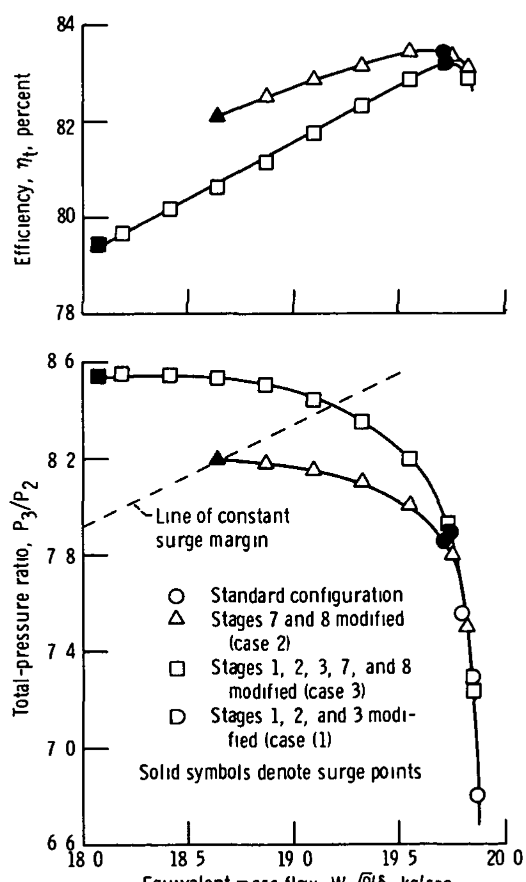

Figure 11 - Effects of treatments of front and/or rear stages of J85 compressor at 100-percent speed

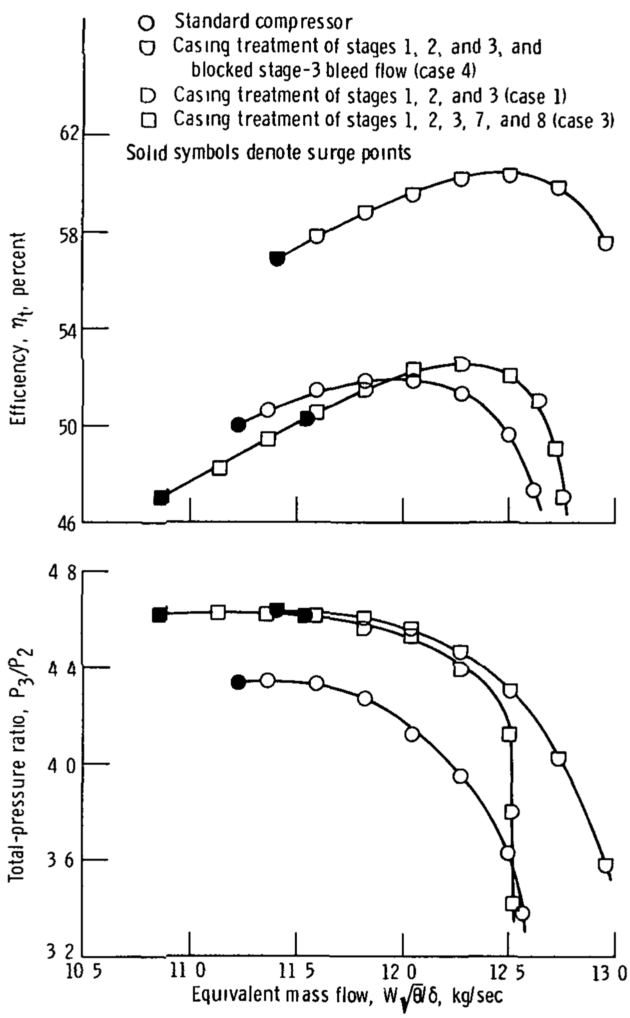

Figure 12 - Effects of casing treatments of various stages and added effect of bleed-flow blockage of stage 3 of J85 compressor at 80-percent speed

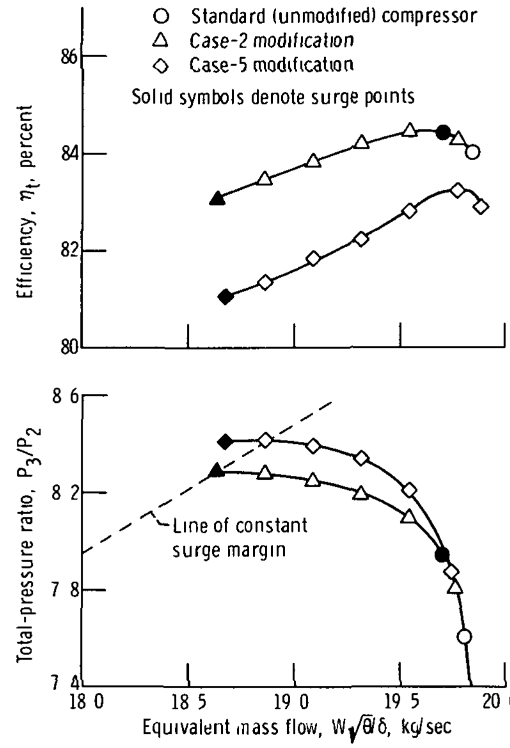

Figure 13 - Comparison of results from casing treatment of front and/or rear stages and from standard J85 compressor at 100-percent speed

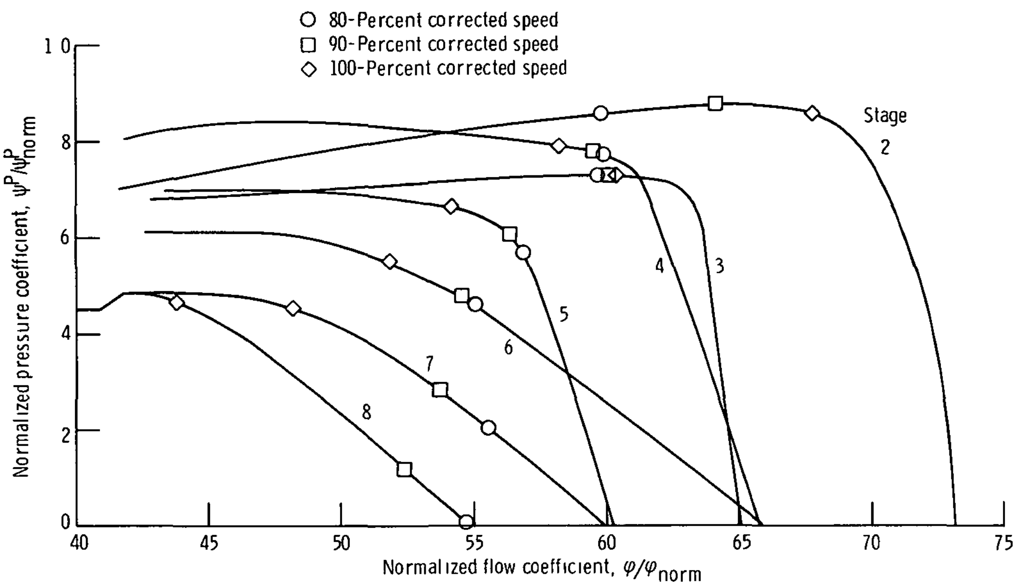

Figure 14 - Stage-by-stage normal operating points at various speeds for standard J85 engine

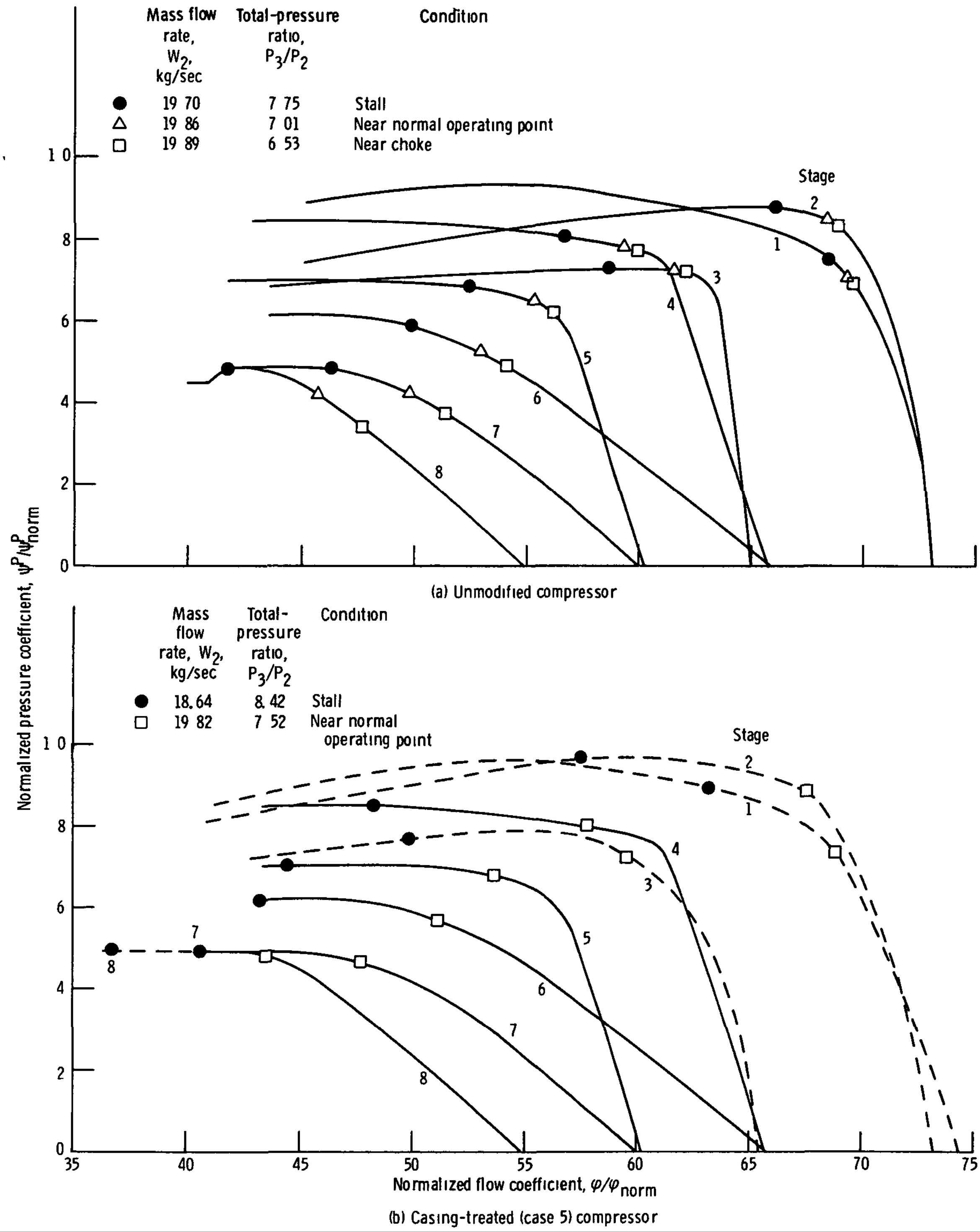

Figure 15 - Shifts in operating points of various stages of J85 compressor at 100 percent speed

NASA-Langley, 1972 — 1 E-6920

"The aeronautical and space activities of the United States shall be conducted so as to contribute . to the expansion of human knowledge of phenomena in the atmosphere and space The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof"

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge

TECHNICAL NOTES Information less broad in scope but nevertheless of importance as a contribution to existing knowledge

TECHNICAL MEMORANDUMS Information receiving limited distribution because of preliminary data, security classification, or other reasons

CONTRACTOR REPORTS Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge

TECHNICAL TRANSLATIONS Information published in a foreign language considered to merit NASA distribution in English

SPECIAL PUBLICATIONS Information derived from or of value to NASA activities Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies

TECHNOLOGY UTILIZATION PUBLICATIONS Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys

Details on the availability of these publications may be obtained from

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546